DEVELOPMENT AND IMPLEMENTATION OF IMPROVED CODED OFDM SYSTEM USING SDR PLATFORM

BY

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LIST OF ABBREVIATIONS

2G	2^{nd} Generation
ACM	Adaptive Coding and Modulation
ADC	Analog-to-Digital Converter
ADSL	Asymmetric Digital Subscriber Line
AGC	Automatic Gain Control
ARQ	Automatic Repeat Request
ASK	Amplitude Shift keying
AWGN	Additive White Gaussian Noise
BCH	Bose-Chaudhuri-Hocquenghem codes
BER	Bite Error Rate
BSC	Binary Symmetrical Channel
CC	Convolutional Codes
CCOFDM	Convolutional Coded OFDM
CMD	Command File Generator Block
CCR	Convolutional Codes Rate
CDMA	Code Division Multiple Access

COFDM	Coded OFDM
CP	Cyclic Prefix
CR	Code Rate
CSI	Channel State Information
ECC	Error Correcting Code
dB	Decibel
DFT	Discrete Fourier Transform
DP	Development Platforms
DSP	Digital Signal Processor
FDD	Frequency Division Duplex
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FSK	Frequency Shift Keying
GF	Galois Field
GMD	Generalized Minimum Distance
GPP	General Purpose Processor
ICI	Interchannel Interference

IDFT	Inverse Discrete Fourier Transform
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
IFFT	Inverse Fast Fourier Transform
ISI	Inter-symbol Interference
LDPC	low Density Parity Check
LFSR	Linear Feedback Shift Register
LSR	Linear Shift Register
lsb	Least Significant Bit
LOS	Line O*f* Sight
MBS	Mobile Broadband Services
MB-OFDM	Multiband-OFDM
ML	Maximum-Likelihood
MIMO	Multiple Input Multiple Output
msb	Most Significant Bit
MMSE	Minimum Mean-Squar-Error
MQAM	Multiple Quadrature Amplitude Modulation
NLOS	Non-Line of Sight

OFDM	Orthogonal Frequency Division Multiplexing
PAR	Peak to Average Ratio
PCE	Probability of Codeword Error
Pdf	Probability Density Function
Psd	Power Spectral Density
PSK	Phase Shift Key
PHY	Physical Layer
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
R & D	Research and Development
RF	Radio Frequency
RS	Reed-Solomon Code
RS-CC	Reed-Solomon and Convolotional Code
RS-CCOFDM	Reed-Solomon and Convolotional Coded OFDM
RSCOFDM	Reed-Solomon Coded OFDM
RTW	Real-Time Workshop
SDR	Software-Defined Radio
SFF	Small Form Factor

SFH	Slow Frequency Hoping
SISO	Soft-Input, Soft-Output
SNR	Signal to Noise Ratio
UWB	Ultra Wide Band
TLC	Target Language Compiler
WSSUS	Wide Sense Stationary Uncorrelated Scattering
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
XOR	Exclusive OR Gates

LIST OF SYMBOLS

a	Coefficient of polynomial expression for Galois Field element
B_c	Coherence bandwidth
BN_o	The Noise Inside the Bandwidth
c	Output of CC
CR	The Code Rate of any Code
d_{min}	Minimum Distance of Codeword
d_{ri}	The Distance between L Dimensional Received Vector
$E(x)$	The Error Pattern of RS Codes
e_i	Locations of Error in RS Codeword
f	Frequency Index
f_d	Doppler Shift
h	Column Index of Interleaver
H	Number of SNR Regions of ACM
k	Number of Information Symbols or Bits
K	Constraint Length of CC
L	Dimensional Received Vector
$\acute{L}$	Tracking the Order of the Equations for Berlekamp's Algorithm

m	Number of Bits per Symbol
$M(x)$	The message to be Encoded in RS Codes
n	Number of Codeword symbols
N	Number of Elements in Galois Field
$n(t)$	Sample Function of Noise
N_c	Number of Subchannel of an OFDM
N_o	One-Sided psd
P	Probability of Error
p	Puncturing Matrix
$P(.\|.)$	Conditional Probability
$P(x)$	Primitive Polynomial
$q(x)$	The Quotient of Division Process RS Codes
$Q_i(x)$	The Quotient of Dividing Process for RS
$R(\alpha^i)$	The Symbol Received Codeword
$r(t)$	The Received Signal
$r(x)$	The Remainder of Division in RS Codes
$R(x)$	The Received Codeword
S	Number of Memory in CC

$s(t)$	The Transmitted Signal
S_i	The Syndromes Polynomial
T	IFFT Input symbol Period
t	The Symbol Error Correcting Capability of RS Codes
t'	Time Index of CC
$T(x)$	The Transmitted Codeword in RS Codes
T_c	Coherence Bandwidth
T_g	Length of CP
T_s	Symbol Time Duration
T_x	The Starting of Sampling Period
v	Number of Errors in RS Codeword
v_d	Velocity of Mobile Unit
w	Row Index of Interleaver
x	Location in Polynomial Equation
x_{ri}	Code Subvector of rth Message Sequence for ith Branch Level
Y_i	Error Values at Each Location of RS Codeword
Ꝁ	The Step parameter of Berlekamp's Algorithm
$\tau_{\max}$	Maximum Multipath

σ^2	The Variance of the Noise
τ	Delay spread
σ_τ	Root-Mean-Square Delay Spread
$\sigma(x)$	Error Locator Polynomial of RS Codes
$\phi_i(t)$	Complex- valued function for interval (t_1), i is integer.
$\phi_j(t)$	Complex- Valued Function for Interval (t_2) , j is Integer
α	Primitive Element
β	Received Signal Length
$\Lambda(x)$	Alternative Form of Error Locator Polynomial
$\Omega(x)$	Error Value Polynomial for RS Codeword
$\Lambda^{'}(X_j^{-1})$	Derivative of $\Lambda(x)$
γ	Time Index
Ψ	Standard Deviation

PEMBANGUNAN DAN IMPLEMENTASI PENAMBAHBAIK KOD SISTEM OFDM DENGAN MENGGUNAKAN PLATFORM SDR

ABSTRAK

Peningkatan permintaan untuk sambungan tanpa wayar berkelajuan tinggi dengan kos rendah merupakan cabaran baru bagi para pereka bentuk sistem komunikasi, untuk melaksanakan penyelesaian yang meningkatkan kadar data supaya lebih berkesan dengan memanfaatkan sumber radio yang terbatas pada tahap kerumitan yang rendah. Kod Mudahsuai dan Modulasi (ACM) memanfaatkan keanjalan kod saluran dan gugusan dalam Pemultipleksan Pembahagian Frekuensi Ortogonal (OFDM) untuk mendapatkan kelajuan data yang lebih tinggi. Teknik ini menggunakan beberapa modulasi dan skim pengekodan untuk segera menyesuaikan diri dengan kepelbagaian dalam saluran Isyarat untuk Nisbah Hingar (SNR), dengan demikian memaksimumkan daya pemprosesan sistem dan meningkatkan prestasi Kadar Kesilapan Bit. Di sisi lain, sistem OFDM terjejas akibat gangguan antara-simbol (ISI), terutamanya dalam persekitaran komunikasi bergerak. Masalah ini dapat diatasi dengan meningkatkan tempoh simbol individu untuk setiap subpembawa bersama-sama dengan penggunaan masa adang. Namun demikian, hal ini tidak dapat menyelesaikan masalah sepenuhnya dalam saluran ketidakjelasan multi-laluan, kerana semua subpembawa akan tiba di penerima dengan amplitud yang berbeza. Malangnya, beberapa subpembawa mungkin akan hilang sepenuhnya kerana jurang ketidakjelasan yang tinggi. Oleh kerana itu, meskipun sebahagian besar subpembawa boleh dikesan tanpa kesilapan, keseluruhan BER akan sangat didominasi oleh beberapa subpembawa SNR buruk. Untuk menghilangkan masalah

ini, sistem berasaskan OFDM biasanya menggunakan teknik khas seperti pembetulan kesalahan pengekodan. Pelbagai kaedah pengekodan diadopsi oleh banyak standard untuk mengurangkan kesan memilih saluran frekuensi yang menyebabkan kesalahan bit terjadi di dalam keadaan letupan. Reed-Solomon (RS) dan Kod Konvolusi (CC) sangat berguna untuk pembetulan kesilapan-letup, begitu juga berkesan untuk saluran jurang ketidakjelasan yang tinggi. Hal ini berguna untuk meningkatkan prestasi OFDM. Tesis ini pada permulaannya mempersembahkan RS dan CC sebagai kod fleksibel untuk meningkatkan prestasi OFDM sebagai kod tunggal dan juga kod rangkaian. Selanjutnya satu ACM berdasarkan rangkaian RS dan CC untuk sistem OFDM direka. Akhirnya, perkakasan dilaksanakan dengan menggunakan faktor bentuk kecil (SFF) perisian menyatakan radio (SDR) platform-platform pembangunan (DP), untuk membandingkan prestasi penghantar terima jalur asas sistem OFDM untuk RS, CC dan RS-CC dengan saluran AWGN berdasarkan IEEE 802.16 Worldwide Interoperability untuk Microwave Access (WiMAX). Dengan perkakasan yang dicadangkan, BER akan merosot sebagai mana SNR meningkatkan dari 0 untuk 50 dB, menjadikan reka bentuk mudah dan sempurna untuk mana-mana jenis aplikasi SDR. Semua kerja-kerja tersebut sebelumnya dipersembahkan menggunakan perisian Matlab. Keputusan simulasi menunjukkan yang bit perantara-lembar menambah-baikan CC-OFDM sebanyak 9dB dan menurunkan RS-OFDM sebanyak 1.4 dB pada 10^{-4} BER. Skim cadangan RS-CC dengan OFDM juga boleh mencapai penambahan kod sebanyak 19 dB dibandingkan dengan sistem yang tidak dikod OFDM pada 10^{-4} BER, dan mengatasi sistem yang serupa dengan kod tunggal sebanyak 8dB. Tambahan pula, peningkatan baru menunjukkan persembahan terbaik pada SNR rendah. Keputusan juga menunjukkan sistem OFDM itu dengan ACM memberi persembahan terbaik terhadap kadar bit; reka bentuk yang dicadangkan boleh mencapai kadar penambahan bit 7 Mbps pada SNR yang tinggi dibandingkan dengan skim yang tidak adaptif untuk 10^{-2} mensasar BER.

DEVELOPMENT AND IMPLEMENTATION OF IMPROVED CODED OFDM SYSTEM USING SDR PLATFORM

ABSTRACT

The increasing demand for high speed wireless connectivity at low cost poses new challenges for communication system designers, to implement solutions that increase the data rate by utilizing the limited radio resources more efficiently at a low additional complexity. Adaptive Coding and Modulation (ACM) exploits the flexibility of channel coding and constellation in Orthogonal Frequency Division Multiplexing (OFDM) to obtain higher data rates. This technique employs multiple modulation and coding schemes to instantaneously adapt to the variations in the channel Signal to Noise Ratio (SNR), thus maximizing the system throughput and improving Bit Error Rate (BER) performance. On the other hand, OFDM system suffers from inter-symbol interference (ISI), especially in mobile communication environments. This problem may be tackled by increasing the individual symbol duration for each subcarrier together with the use of guard time. Nevertheless, this does not solve the problem completely in multipath fading channel, because all subcarriers will arrive at the receiver with different amplitudes. Unfortunately, some subcarriers may be completely lost because of deep fades. Hence even though most subcarriers may be detected without errors, the overall BER will be largely dominated by a few subcarriers with bad SNR. To eliminate this problem, OFDM based systems usually employ a special technique like error correction coding (ECC). Various coding methods are adopted by many standards to mitigate the effects of frequency selective channel which causes bit errors to occur in burst. Reed-Solomon (RS) and convolutional codes (CCs) are particularly useful for burst- error correction that is, they are effective for deep fades channel. It is useful to improve the OFDM performance. This thesis first presents the RS and CC as flexible codes to improve OFDM performance as single codes, and as concatenation codes. Subsequently an ACM based on concatenation of RS and CC for OFDM system is designed. Finally, the hardware is implemented using the small form factor (SFF) software-defined radio (SDR) development platforms (DP), to compare the performance of the OFDM system baseband transceiver for RS, CC and RS-CC with AWGN channel based on IEEE 802.16 Worldwide Interoperability for Microwave Access (WiMAX). By the proposed hardware, the BER decreases as the SNR increases from 0 to 50 dB, making the design simple and acceptable for any type of SDR application. All the aforementioned works are performed by using Matlab tools. The simulation results show that the bit interleaver improves CCOFDM by *9* dB and degrades RS-OFDM by *1.4*dB at 10^{-4} BER. Also the proposed scheme of RS-CC with OFDM could achieve a code gain of *19*dB compared with uncoded OFDM system at 10^{-4} BER, and outperforms the same system with single code by *8*dB. Moreover the new improvement in the proposed research has best performance at low SNR. The results also show that OFDM system with ACM gives best performance with respect to bit rate; the proposed design could achieve about *7* Mbps bit rate gain at high SNR compared with non-adaptive scheme for 10^{-2} target BER.

CHAPTER 1

INTRODUCTION

1.1 Motivation

Several technologies are considered to be candidates for future applications, such as Orthogonal Frequency Division Multiplexing (OFDM), which is a special form of multi-carrier transmission where all the subcarriers are orthogonal to each other. OFDM promises a higher user level of implementation complexity (Chen et al., 2009). On the other hand, OFDM is very sensitive to frequency errors. Its performance also suffers from distortions, and Inter-Symbol Interference (ISI) caused by multipath in band-limited (frequency selective) time dispersive channels, causes bit errors at the receiver. ISI has been recognized as the major obstacle to high speed data transmission over mobile radio channels. The transmitted signal that is launched into the wireless environment arrives at the receiver along a number of distinct paths, referred to as multi-paths (Lawrey, 2001a). (See Figure 1.1). In addition, it exhibits a high peak-to-average ratio. In other words, there is a problem of extreme amplitude of the transmitted signal.

The OFDM signal is basically a sum of N_c complex random variables, each of which can be considered as a complex modulated signal at different frequencies. In some cases, all the signal components can add up in phase and produce a large output and in some cases, they may cancel each other producing zero output. Thus the Peak-to-Average Ratio (PAR) of the OFDM system is very large (Muhammad, 2005).

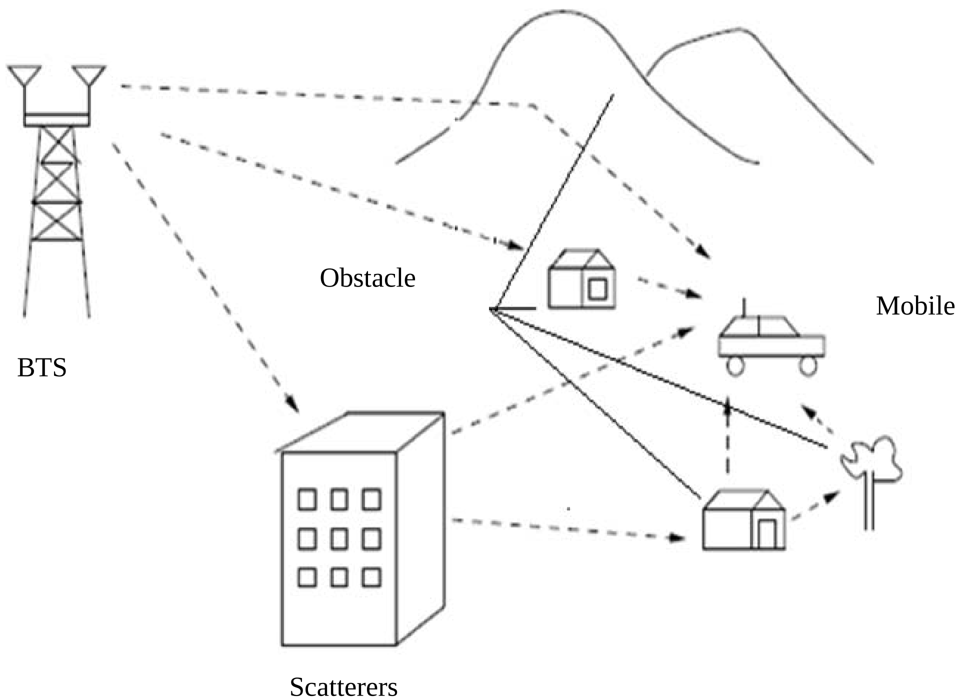

Figure 1.1: Wireless propagation environment.

To reduce these effects, channel coding is required which provides for forward error correction (FEC). This enables the receiver to correct the errors that have occurred in the transmission path (Lu et al., 2006). Channel coding selectively adds redundancy to the source encoded data to permit error detection/ correction at the receiver.

The channel encoding process may be considered as reverse process of source encoding in the sense that source encoding compresses the input information by reducing redundancy in it while the channel coding introduces the source encoded information. However, this redundancy is added as a result of channel coding is more logical and controlled in the nature than the inherent redundancy in the original information, and hence can be effectively utilized by the receiver to detect as well as correct errors in the received sequence (Rappaport, 2002).

The growing demand for all types of services aims for the design of increasingly more intelligent communication systems, capable of providing spectrally efficient and flexible data rate access. These systems are able to adapt and adjust the transmission parameters based on the link quality, improving the spectrum efficiency of the system, and reaching, in this way, the capacity limits of the underlying wireless channel (Goldsmith, 2005). The motivation of this thesis is to offer convenient remedies to overcome the drawback of OFDM system.

1.2 Problem Statements

Reliable data communication on wireless channels and high speed data transmission over mobile radio channels is a very challenging task that involves various different problems. Orthogonal Frequency Division Multiplexing (OFDM) as a candidates for future applications which promises a higher user level of implementation complexity, However OFDM performance suffers from distortions, and Inter-Symbol Interference (ISI) caused by multipath in band-limited (frequency selective) time dispersive channels, causes bit errors at the receiver.

It is necessary to choose a coding technique which provides Forward Error Correction (FEC) to mitigate OFDM influences which stems from multipath fading channel, high speed data rate, and frequency Doppler Shift emanated due to user movements that increases performance with minimal trade-offs in power and bandwidth.

The increasing demand for high speed wireless connectivity at low cost poses new challenges for communication systems designers to implement solutions that is to reduce the weight and cost. New coding schemes for low BER with lower decoding complexity is required for data communication services in order to meet higher capacity and quality demands with acceptable performance criteria over a hostile mobile radio channel.

Therefore real-time decoding without noticeable information losses typically require. When high coding gain is required concatenated coding is approach to improve the error performance of code for a large constraint length with lower decoding complexity for this reason channel coding has become widespread in the design of digital transmission systems.

Reed-Solomon (RS) and convolutional codes (CCs) are particularly useful for burst-error correction that is, they are effective for deep fades channel. It is useful to improve the OFDM performance, but the range of SNR that achieves suitable BER is relatively high. In addition the performance is still worse with lower SNR, therefore there is need for further improvement especially when deals with mobile communication which is highly corrupted due to multipath and admissibility of the line of sight (LOS) and offer convenient remedies to overcome the drawback of OFDM system.

Significant difficulties faced by the communication designer to understand the theoretical side of OFDM systems. This causes a gap between theoretical and practical sides. Digital signal processor (DSP) is one of the most important processing method providers new software application in improving the reliability of digital transmission. Furthermore, new emerging technology of defined radio platform can provide a real–time communication where the message may not be delayed, also the additional of redundant bits dictates a faster rate of transmission (faster signaling, less energy per channel symbol and more errors out of the demodulator) which of course means more bandwidth.

1.3 Research Objectives

The severe channel conditions have placed a major obstruction upon designing efficient transmission systems over wireless environments. Objectives of the research are listed below:

1. To develop a novel coded OFDM (COFDM) technique, to improve OFDM system drawbacks and its features by using Reed-Solomon codes and convolutional codes (RS-CC), and combining these two codes in a concatenation technique.
2. To design an Adaptive Coding and modulation system (ACM) to improve OFDM system based on the concatenated RS-CCOFDM WiMaX protocol. Each multistage level of mapper design, involves specific parameters of codes pairing with appropriate level of constellation, and is controlled by ACM system design related to channel condition, to increase the amount of received bit rate.
3. To implement and analyze the proposed COFDM system in real time application using software-defined radio platforms.

1.4 Research Scope

The requirement for real-time processing indeed poses challenges on implementing channel coding algorithms. Trade-off between the complexity and the effectiveness of channel coding algorithms should be taken into consideration in this work. The Small Form Factor Software defined Radio Development Platform (SFF SDR DP) is conceived and designed to be used in the development of applications in the field of software-defined radio. By separating the base band, IF, and RF from one another as distinct modules in order to extend the radio development capabilities and optimize costs and power consumption. This research work is more focus in the advanced signal processing techniques involving channel coding technique algorithms, the 4 G mobile transmissions (OFDM) System, and adaptive modulation techniques that can be easily implemented without necessitating major hardware changes in the transceiver.

1.5 Summary of Contribution

The original contribution in this work is to design of a new ACM system, based on developed concatenation of RS-CCOFDM system to increase the bit rate. Multilevel mapper is a new technique comprised of coding, decoding and feedback mechanism. This involves the combination of adaptive coding and modulation (ACM). This combination gives more flexibility to choose specific parameters to match channel conditions, offers better spectral efficiency and power economics and improve the bit error rate (BER) performance. This work also investigates new way of hardware implementation. New real time fills the gap between theoretical and practical sides of OFDM system by applying channel coding as new technique. The hardware is implemented using the small form factor (SFF) software-defined radio (SDR) development platforms (DP) to improve the system. The contribution of this thesis can be classified into three categories.

I. Conventional OFDM

This is an approach to improve some features of conventional OFDM system and to rectify its drawbacks. The system is tested under Rayleigh fading channel, assuming that the synchronization sometimes is lost. A relatively small size of FFT (2^6) under good channel conditions achieved good gain compared with bad channel conditions, the amount of information is increased relative to the size of FFT.

II. Single Carrier Transceiver

In the second testing system design, the features of block and CCs are exploited to overcome the drawbacks of each other and the performance of each code is observed in order to choose the effective parameters, this technique is then applied for OFDM system over selective fading channel, to improve the system. Hence, the benefit of increased redundancy would be the improvement in bit-error performance. Making the choice of appropriate coding and modulation techniques that are available in improving the complexity of a high-speed implementation, increases with redundancy especially for high-speed devices.

III. Coded OFDM

The Contribution of this subsection can be further classified into three categories:

1. **Coded OFDM with Single Code are Categorize as Below:**

A. Reed-Solomon Coded OFDM (RSCOFDM)

The improvements stem from applying RS codes making the OFDM system more robust to combat frequency selective fading which stem from multipath channels. Therefore such a code is active for various types of channels, and offers a good improvement at BER level for a variable-rate coding scheme that depends on the channel conditions with various ranges of SNR in order to offer optimal error protection levels to the users. The technique is employed in IEEE802.16e standard.

B. Convolutional Coded OFDM (CCOFDM)

The advantage of applying CC with OFDM system gets significant benefit without affecting any of its original structure. CC improves the OFDM system under various conditions over Rayleigh fading and AWGN without fading channel, at high SNR. However, it will be an advantage to choose convenient code rate that has trade-off between code gain and efficient spectrum with low code rate and bandwidth expansion, where it holds the constraint length at fixed value. Therefore, performance of CC is still worse if the constraint length is increased. Otherwise small constraint length gives significant improvement at low SNR.

2. **Coded OFDM with Concatenated Codes (RS-CCOFDM)**

Some new design and parameters are established in this subsection. These new parameters are expected to yield significant improvement to develop a concatenated code that can perform well, both at low and high SNR. It will reduce the processing time and the memory size and lead to simple implementation.

3. The Effect of Interleaver

However, real-time systems must consider tradeoffs between coding delay and error protection. Therefore, such codes perform poorly in a real-time communication system. The types of such interleavers depend on the nature of structure and its parameters; the delay time is increased with the presence of more than one inter-leaver.

1.6 Thesis Outline

The remaining chapters of this thesis are organized as follows:

In Chapter Two, literature review will be presented to highlight the systems used in this thesis, such as types of Error Correction and Detection codes. RS codes and CC in the communication system are investigated. The performance of interleaved block and CC are also investigated. The concept of concatenated multilevel codes and performance of conventional OFDM over the Size of FFT are presented in this chapter. ACM literature review, the issues of adaptive coding and modulation (ACM) associated with the previous works compared with the ACM of the present study are also presented. Finally implementation of communications systems on SFF SDR DP related with this work is presented.

In Chapter Three methodologies of proposed OFDM and channel coding scheme are presented, also this chapter describes an OFDM transceiver. The channel model was described, which is used to simulate the performance of the OFDM system. In addition the RS and CC theory is presented as optimum channel coding, followed by brief explanation about concatenated codes, and interleaver. Finally Adaptive Transmission Technique is presented in this chapter.

In Chapter Four development of the proposed system is presented. This chapter also provides a brief review on the evaluated conventional OFDM system model without any code, and with single code including RS, or CC. Conventional concatenation of RS –CC come after that, with OFDM system. Subsequently the proposed RS-CCOFDM is presented, and ACM based on the proposed COFDM transceiver is also given in this chapter.

Chapter Five is the core of this dissertation. Results and discussion for the proposed system schemes are presented, followed by evaluation of conventional OFDM system with no code, with single and concatenated codes, to enlighten the amount of improvement stem from adding each one.

Chapter Six presented new technique in analyzing developed software system design through an implementation method based on RS-CCOFDM. Real time hardware implementation COFDM are done by the small form factor (SFF) software-defined radio (SDR) development platforms (DP), making the design simple and perfect for any type of SDR application.

Chapter Seven contains conclusions and suggestions for future research.

Appendix A gives the procedure of RS decoding process and worked example. **Appendix B** includes the application of Viterbi algorithm.

Appendix C includes, the implementation and applications in real-time by the SFF SDR DP.

Appendix D presents RS codes fundamentals and description of paramount features.

Appendix E describes the performance analysis of CC.

Appendix F provides the design of digital communication systems.

Finally Appendix G includes Matlab M-Files Simulation Programs.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

Reliable data communication on wireless channels is a very challenging task that involves various different problems. In contrast to fixed line communication channels, radio channels are usually described as space, time and frequency varying channel. This is due to the severe conditions that a transmitted signal is subjected to. Radio communication systems should be tolerant to the effect of fading of the signal due to propagation over multipath or due to shadowing (Mahmoud, 2008). The incoming signal may also suffer from Inter Symbol Interference (ISI) due to multipath propagation of the signal. Also, the wireless channel is very noisy due to interference from other communication systems and the background noise (Al-Askary, 2006).

Mobile data communication is even more challenging. In addition to the problems mentioned above, that are common to all wireless systems, there are further considerations. For example, a moving mobile unit might lead to total change of the channel conditions which requires continuous measurement and updating of the Channel State Information (CSI) and adaptation of the coding/modulation strategy to the new conditions. There are also some requirements that stem from the nature of the services in mobile communications. One of these requirements is that the mobile units should be small and energy efficient. Therefore, there is relatively little margin for energy consuming extensive signal processing. A seamless and uninterrupted service quality for a user regardless of the system he/she is using will be one of the main goals of future systems (Tachikawa, 2003).The expected systems will require an extensive amount of bandwidth per user. Figure 2.1shows the current and future mobile systems. The general trend will be to provide higher data rates and greater mobility.

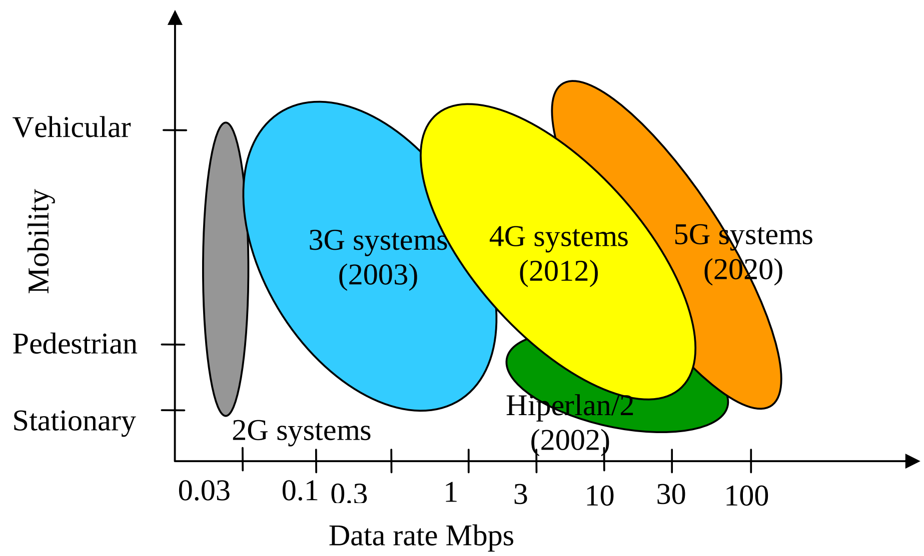

Figure 2.1: Current and Future Mobile Systems. (Tjelta *et al*., 2001and DoCoMo, 2000).

2.1 Motivation Toward Error Detection and Correction Techniques

The basic purpose of error detection and error correction techniques is to introduce redundancies in the data to improve wireless link performance. The introduction of redundant bits increases the raw data rate used in the link hence, increases the bandwidth requirement for a certain data rate. This reduces the bandwidth efficiency of the link in high SNR conditions, but provides excellent BER performance at low

SNR values. A channel coder operates on digital message (or source) data by encoding the source information into a code sequence for transmission through the channel.

Channel coding is a common strategy to make digital transmission more reliable, or, equivalently, to achieve the same required reliability for a given data rate at a lower power level at the receiver. This gain in power efficiency is called coding gain. For mobile communication systems, channel coding is often indispensable. The bit error rate in a fading channel increases, which would require an unacceptable high transmit power to achieve a sufficiently low bit error rate. Channel coding is used with digital data to detect and to correct the errors by selectively introducing redundancies in the transmitted data. The codes that are used to detect errors are called error detection codes, while codes that can detect and correct errors are called error correction codes.

There are several ways to gain performance of an OFDM system, e.g. use of channel equalization, multiple antennas (MIMO) and channel coding. The latter one is the focus of this thesis. Forward Error Correction (FEC) is an effective tool to mitigate OFDM influences which stems from multipath fading channel, high speed data rate, and frequency Doppler shift emanated due to user movements (Maciel and Klein, 2010).

Forward Error Correction coding refers to the class of signal transformations designed to improve system performance by enabling the transmitted signal to better withstand the effects of various channel impairments, such as noise, interference, and fading. Error correction coding is very popular because it is typically a less expensive means of improving performance when compared to other methods such installing higher power transmitters and larger antennas. This is especially true for such modern communications. The improved system performance usually involves system trade-offs such as error-performance versus bandwidth and power versus bandwidth. In digital communication systems that are both bandwidth-limited and power-limited, error-correction coding (often called channel coding) can be used to save power or to improve error performance at the expense of bandwidth. It is necessary to choose a coding technique that increases performance with minimal trade-offs in power and bandwidth (Shannon, 1948b).

2.2 Types of Error Correction and Detection Codes

Among the popular coding techniques are block codes and convolutional codes. These techniques, however, improve system performance at the expense of expanding the bandwidth by an amount proportional to the reciprocal of the code rate. There are two basic types of error correction and detection codes: block codes, and CCs:

I. **In Block Codes**, parity bits are added to blocks of message bits to make codewords or code blocks. In a block encoder, *k* information bits are encoded into *n* code bits. A total of *n*-*k* redundant bits are added to the *k* information bits for the purpose of detecting and correcting errors. One of most important types of block codes is Reed-Solomon (RS) codes. The ability of a block code to correct errors is a function of the code distance. Many families of codes exist that provide varying degrees of error protection.

II. **Hamming Codes** were among the first of the nontrivial error correction codes. These codes and their variations have been used for error control in digital communication systems. There are both binary and nonbinary Hamming codes. A binary Hamming code has the property that, $(n,k) = (2^m - 1, 2^m - 1 - m)$, where k the number of information bits is used to form a n bit codeword, and m is any positive integer. The number of parity symbols is $n - k = m$.

III. **Cyclic Codes** are a subset of the class of linear codes which satisfy the cyclic property. As a result of this property, these codes possess a stirring amount of structure which can be exploited. Encoding for a cyclic code is usually performed by a linear feedback shift register based on either the generator or parity polynomial (Hamming, 1950).

IV. **BCH Codes** are among the most important block codes since they exist for a wide range of rates, achieve significant coding gains, and can be implemented even at high speeds. The block length of the codes is $n = 2^m - 1$ for $m \geq 3$, and the number of errors that they can correct is bounded by $t < (2^m - 1)/2$. The binary BCH codes can be generalized to create classes of non-binary codes which use m bits per code symbol. The most important and common class of non-binary BCH codes is the family of codes known as RS codes (Gabay et al., 2007).

2.3 Performance of Parallel Concatenated Codes

The most recent breakthrough in coding theory is the discovery of a class of codes called turbo codes that exhibit near Shannon-limit performance with iterative decoding algorithms (Berrou et al., 1993). The astounding performance of turbo codes resulted in a surge in the research activity on iterative de-coding. For example, Gallager's low density parity check (LDPC) codes discovered with iterative decoding in the 60's by Gallager (1962), has drawn tremendous attention in the past few years. Although the above mentioned turbo codes have excellent bit error performance, there still exists some problems. First of all, their error performance tails of, or exhibits an error “floor" at high signal-to-noise ratio (SNR). Moreover, the complexity of the required soft-input, soft-output (SISO) decoder is such that a cost-effcient decoder was unavailable for most commercial applications (Wadayama, 2005). For these reasons, RS codes are still widely employed in many practical applications because of its efficient decoder implementation and excellent error correction capabilities (Reed and Solomon, 1960).

McEliece et al., the first describes the close connections between the iterative turbo decoding algorithms with Pearl’s belief propagation algorithm. Turbo principle as an example is a strategy exploiting the iterative process with significantly shorter block lengths. The performance of parallel and serial concatenated convolutional codes are presented by Yuan et al. (2002) based on the derived analytical bounds are compared over independent fading channels on frequency-nonselective Rician fading channels. Soft-output Viterbi algorithm (SOVA) decoding methods iterative decoding methods, with and without channel state information, on fading channels with and without CSI are considered. Yuan et al. (2002)concluded that the serial concatenated codes perform better than parallel concatenated codes on correlated fading channels. Channel encoder is considered parallel and serial concatenated convolutional codes. Encoder schemes are shown in Figure 2.2 and Figure 2.3, respectively. Random interleaver is linked between the inner encoder and the outer encoder. Simulation results observed that the parallel code has a better performance at low SNR than the serial one but the serial code outperforms the parallel code at high SNR, as shown from the graphs in Figure 2 .4.

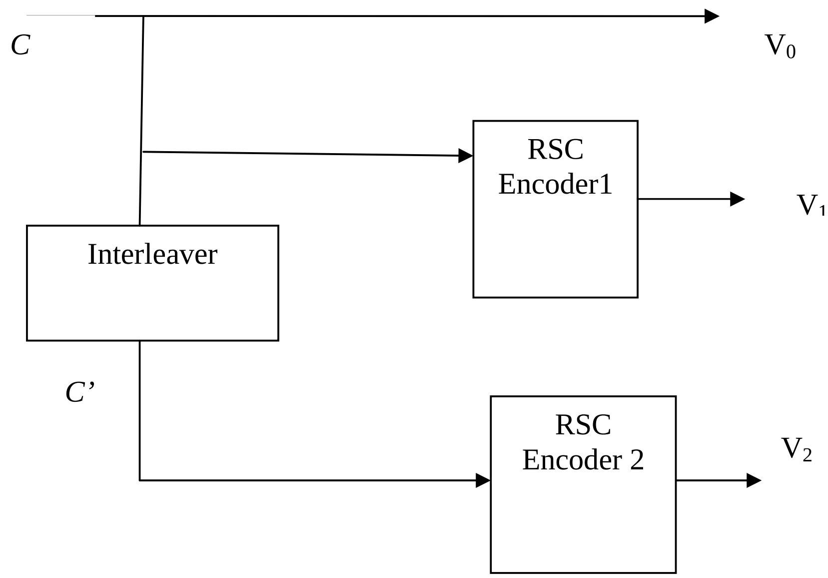

Figure 2.2: Turbo Encoder Implemented by Yuan et al. (2002).

Figure 2.3: Serial Concatenated Encoder Implemented by Yuan et.al (2002).

Figure 2.4 show the performance comparison for the four-state, rate 1/3 parallel and serial codes on an independent Rayleigh fading channel, the message length N = 1024and 4096. Rahman et.al (1999) presented the performance of serial concatenated convolutional code (SCCC) in frequency selective Rayleigh fading (FSRF) channel.

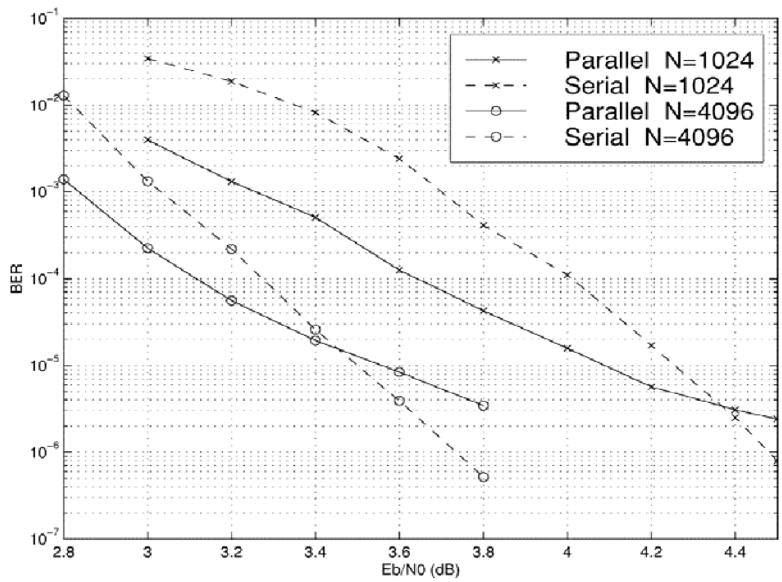

Figure 2.4: BER Performance Parallel Concatenated Codes over Serial Codes on Rayleigh Fading Channel (Yuan et al., 2002).

The decoding procedure considered a block called SISO (Soft-Input Soft-Output, used within the iterative decoding algorithm. The BER improvement is low compared to higher iteration with the increment in SNR; increase in number of iteration does not improve gain but provides a BER improvement, while the performance of parallel concatenated interleaved codes is investigated by Lal et.al (1999) for high-bit-rate data transmission in a wideband DS-CDMA system. The authors demonstrated that turbo codes introduced lower coding gain when channel correlation is increased.

In order to improve the performance of OFDM based wireless communications several papers are available in literature that deals with different coding schemes to improve the performance of multicarrier wireless communication systems.

A concatenated coding scheme over different channel conditions investigated by Shahana et al. (2008),which used the Redundant Residue Number System (RRNS) code as the outer code and a convolutional code as the inner code. The BER performances is significant improvement for the proposed RRNS-Convolutional Concatenated coding (RCCC) scheme in presence of additive white Gaussian noise and multipath delay spread by exploiting the inherent properties of RRNS. The authors concluded that the proposed coding scheme makes the OFDM system more robust against multipath effects, timing errors, and to reduce the PAPR without significant increase in BER for the RCCC OFDM system.

2.4 RS Codes In the Communication Systems

Digital communications possess the ability to detect and correct errors introduced by the channel**.** The realm of coding theory is a rich and interesting field. A major pioneer and the father of modern information theory was Claude Shannon. Shannon showed for an Additive White Gaussian Noise (AWGN) channel that the probability of error could be made vanishingly small, provided the data rate is less than or equal to the channel capacity, this proof used randomly generated code words and sub-optimal jointly-typical decoding (Gallager, 1962).

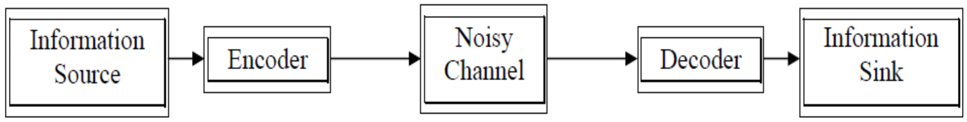

Figure 2.5: Schematic Diagram of Basic Structure of Communication System.

Figure 2.5 shows the block diagram of basic structure of a communication system. Shanon (1948a) had shown that arbitrarily reliable communication is possible as long as the signal transmission rate does not exceed a certain limit called the channel capacity. This stimulated numerous research efforts on error control coding.

Following the first class of error control codes, namely Hamming codes, powerful algebraic codes such as Golay codes, Bose-Chaudhuri-Hocquenghem (BCH) codes, and RS codes were found. As the coding theory evolved, various important properties of codes were identified and studied, such as minimum distance and weight distribution (Whitaker et al., 1991).

The discovery of CCs, which were originally called recurrent codes, was another important landmark in the history of error control coding. CCs have many important properties such as the existence of efficient encoding and decoding algorithms and the impressive performance over AWGN channels. Another important landmark of error control coding theory was the discovery of concatenated coding schemes.

More important discovery was by Forney (1973), who showed that the weakness of CCs against bursty errors could be compensated by serially concatenating a CC with an RS code. RS codes as recurrent codes are block-based error correcting codes with a wide range of applications in digital communications and storage. RS is based in finite field arithmetic, an example of RS code for the Asymmetric Digital Subscriber Line (ADSL) application is implemented by (Shih, 2000), encoding and decoding parameters of symbol width (m=8), message length (k=239), block length (n=255), and maximum capability of error correction (t=8) in the generator was investigated.

Shih (2000) demonstrated that RS codes could achieve a largest possible minimum distance for the given block and information length. The major advantage of RS codes is that the code can correct up to t random symbol errors within a block no matter how many bits are in error in each symbol. The disadvantage of this method is however, RS codes send n symbols in every k input symbols; this expands the system bandwidth utilization, and imposes more noise to the system. As a result, the SNR at the input to the demodulator will be reduced to k/n of uncoded system. Figure 2.6 shows the system block diagram of FEC code using RS code in the communication system used by Shih (2000).

Shih had also demonstrated that the ADSL transmitter and receiver each have two associated paths. The main advantage between the two is that the interleaved path contains an interleaving function in the transmitter and de-interleaving function in the receiver, whereas the fast path does not. This is the advantage of this method.

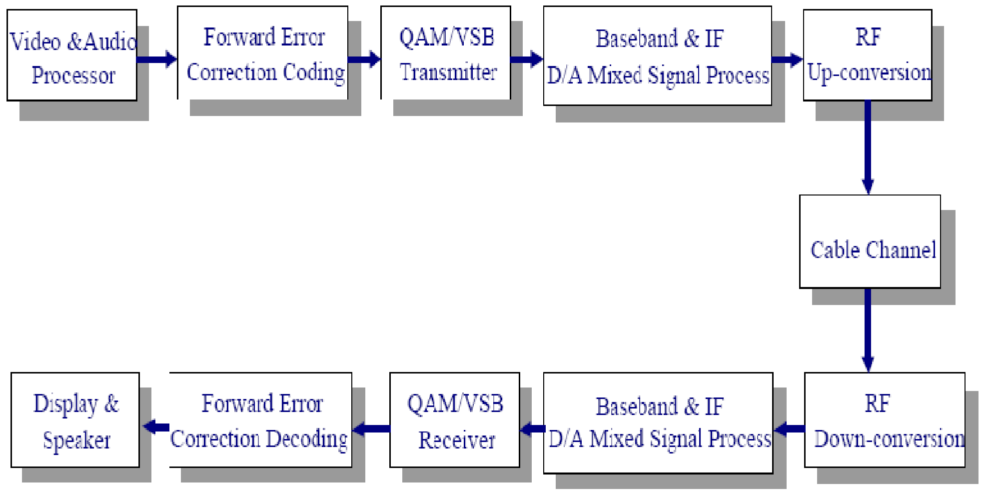

Figure 2.6: FEC Using RS Code in the Communication System (Shih, 2000).

Based on Shih's work another researcher (Julien, 2007) presented another example to enhance the Wi-OFDM and DSL application systems. The system model as shown in the Figure 2.7, involved a two level coded structure, used an outer RS code ,level I as a coded bit and level II as uncoded bit, the researcher used the same parameters which was used by Shih (2000).

Julien (2007) has also considered the same major advantage of RS codes (the code can correct up to *t* random symbol errors within a block no matter how many bits are in error in each symbol, so we can here demonstrate the same disadvantages of this method as in the system used by Shih (2000). It was concluded that a RS outer code could not be considered as the best option for more improvement the system in a fading environment.

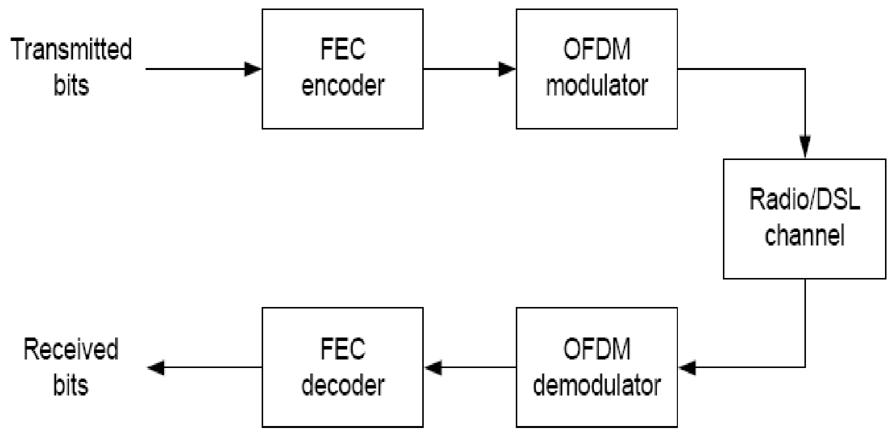

Figure 2.7: FEC Coded OFDM Communication Systems Used by Julien (2007).

Therefore, Julien (2007) has proposed another coding scheme to enhance the Wi-OFDM system in a fading environment with perfect CSI based on a 64-state CC (Wi-Fi and Wimax).
The disadvantage of the last proposed scheme by Julien, was that it still suffered from a high error floor caused uncoded bit. To solve this problem in an AWGN could be mitigated by using outer RS code, instead of a turbo code.

In fact the origin of ECC schemes tracks back to the work of Shannon (1948b) who demonstrated the fundamental principle of error-correction coding schemes. He had shown in this work that even though communication channels were subjected to noise and errors, if some amount of redundancy was encoded into the signal errors could be accounted for and corrected at the receiving end.

This led to the development of various encoding schemes, including RS coding. Many optimization techniques that were modified to ensure low-energy operations through the use of several circuit-level energy, were investigated by Bello (1963) and Miller et al. (1981).

For better signal processing performance based on microprocessors, many algorithms had been implemented using DSP microcontrollers to develop various error corrections RS coding schemes. As for ranging RS coding scheme was implemented by Dust (1998) in order to correct errors, the optical drive of CD players was implemented for NASA's wireless deep-space communications.

A study was reported by Al-Lawati et al., (2007) based on RS of 127 symbol codeword and the number of information (k) of 65 symbols to identify for which perfect interleaving of RS codes. The analytical derivation of simulations were implemented using the Berlekamp-Massey decoding algorithm, the channel model was considered a binary additive Markov noise channel.

Al-Lawati et al., (2007) concluded some disadvantages of using interleaving to render the channel memoryless, also they demonstrated that addition of interleaver introduced delay and caused complexity to the system.

Building on previous result, they also demonstrated that, symbol interleaving could be avoided by RS (127, 65) for the probability of codeword error (PCE) chosen was between 10^{-5} and 10^{-1}, On another hand, it is not necessary to use bit interleaver, it also advantageous to avoid the delay time and complexity system, but improved performance can also be achieved.

Edwards et al. (1997) has investigated the bandwidth efficiency coded modulation technique based on the concatenated 2FSK/8PSK modulation with RS (127, k) code, where k is the number of information symbol over GF (128). This modulation scheme was combined with RS-127 symbol, with different numbers of k, and each RS codeword consisted of 127 symbols.

Error detection and error correction by redundant codes was useful in order to reduce the necessary SNR as reported by Hagenauer and Erich (1987). The researchers focused on forward error correction (FEC) coding and demonstrated that the errors which were introduced in the channel for any encoding information could be reduced to any desired level without a severe decrease in transmission rate. Also Automatic Repeat Request (ARQ) design required a much more specific system design.

Another FEC decoding scheme (YHAH-Viterbi) was implemented in the same work by Hagenauer and Erich (1987), and including an interleaver of variable size was tested over simulated and stored fading channels.

The advantages of the method implemented by Hagenauer and Erich (1987), a) it is a robust method to transform bursts into statistically independent errors, b) The burst errors are, in principle, easier to decode than random errors with the same error rate**.**

The disadvantages of this method are : a) The CCs are not directly suitable for the usage on fading channels, because Viterbi as well as sequential decoders are sensitive to bursty errors, b) The interleaving is commonly applied to spread the bursts of error, it destroys the memory of the channel.